

N78-12086

NASA TECHNICAL

MEMORANDUM

TM-75217

PROTECTION OF COOLED BLADES OF COMPLEX INTERNAL STRUCTURE

P. Glamiche

Translation of "Protection d'Aubes Refroidies à Structure Interne Complex," in High Temperature Problems in Gas Turbine Engines, AGARD Conference Preprint No. 229, Middle East Technical University, Ankara, Turkey, Sept. 19-23, 1977, pp. 22-1 thru 22-9.

1. Report No. NASA TM-75217	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle PROTECTION OF COOLED BLADES OF COMPLEX INTERNAL STRUCTURE		5. Report Date October, 1977	
		6. Performing Organization Code	
7. Author(s) P. Galmiche National Institute of Aerospace Studies and Research		8. Performing Organization Report No.	
		10. Work Unit No.	
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94062		11. Contract or Grant No. NASW-2790	
		13. Type of Report and Period Covered Translation	
12. Sponsoring Agency Name and Address National Aeronautics and Space Adminis- tration, Washington D.C., 20546		14. Sponsoring Agency Code	
15. Supplementary Notes Translation of "Protection D'Aubes Refroidies A Structure Interne Complex," in High Temperature Problems in Gas Turbine Engines, AGARD Conference Preprint No. 229, Middle East Technical University, Ankara, Turkey, Sept. 19-23, 1977, pp. 22-1 thru 22-9			
16. Abstract The problem of general protection of cooled blades of complex internal structure has been solved in a simple and reliable manner. The corresponding method recently developed at ONERA, called SF technique, makes possible, in a single operation, the protection of both external and internal surfaces, as well as those of the orifices of cooling air, whatever their diameter. The SF method is most often applied in the case of pack process, at controlled or high activity; its use can be for use on previously uncoated parts, but also on pieces already coated by a thermochemical, chemical or PVD method. In a general way, the respective thickness of external and internal coatings may be precisely predetermined, no parasitic particle being liable to remain inside the parts after application of the protecting treatment. Results obtained to date by application of the ONERA-SF			
17. Key Words (Selected by Author(s)) method are illustrated in the		18. Distribution Statement paper by the presentation and examination of quite a various selection of advanced turbo engines, which were handed over for treatment, followed by tests or operational use, by engine manufacturers or airlines. Unclassified-Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

PROTECTION OF COOLED BLADES OF COMPLEX INTERNAL STRUCTURE

P. Glamiche

National Institute of Aerospace Studies and Research

Introduction

/22-1*

The constant increase in output or thrust of turbo engines in the course of recent years has been accompanied by a constant increase in input temperatures in front of the turbine. The main factors which have made it possible to obtain such improvements are, on the one hand, the use of refractory superalloys having particularly high mechanical strength characteristics at high temperature and, on the other hand, the development of new shapes of cooled pieces which from now on will allow the consideration of turbine input temperatures appreciably greater than the melting points of materials used in the construction of the most advanced stages of the hot turbine of the engines.

In a very general way the improvement in the quality of mechanical strength at high temperature of refractory superalloys, which is directly related to modifications in their chemical composition, as well as the development of new perfected cooling systems have had a tendency in the other direction to bring about a considerable increase in deterioration problems for parts subjected to operational corrosion phenomena at high temperature, more particularly oxidation and sulfuration during thermal cycling [1-4].

The main reasons for the present increase in corrosion problems at high temperature are the following:

a. The necessary reduction in chrome content in the case of nickel based refractory superalloys which have been developed and

* Numbers in the margin indicate pagination in the foreign text.

which are used almost exclusively in the construction of rotor blades, allowing an increase in the γ' hardening phase.

b. The reduced wall thickness of cooled parts and the increased complexity in interior geometry corresponding to the most efficient internal shapes.

c. The occurrence of internal corrosion and cracking, sometimes unforeseeable, and particularly pronounced in the case of cooled blades made of the most advanced refractory superalloys. /22-2

For about 20 years numerous works have been conducted on the research and development of protective coatings which reduce, if not entirely eliminate, the deterioration effects caused by erosion of the heated parts of turbo engines. Efficient methods have been developed, initially to protect traditional parts. They have been constantly improved, then at the same time studied or modified with a view to applying these methods to obtain protection of cooled parts.

The main purpose of this paper is to present the general principles and findings of the new ONERA SF method which has been developed with an aim to providing ultra efficient protection of cooled parts against corrosion and internal cracking, no matter how complex the internal geometry. This method, which can be very generally adapted and the application of which does not require the use of any special equipment, has been studied, developed and tested on actual turbo engine parts, under the best conditions and in a relatively short amount of time after its development because of the interest it aroused as soon as it first appeared. Many engine manufacturers in France and abroad as well as large airline companies have in fact provided the laboratory -- for purposes of testing or treatments -- with a considerable variety of cooled parts of advanced turbojets and

high-power gas turbines. Experiments were carried out on these parts and favorable results were obtained from them.

1 - General Principles for Current Methods of Protecting Refractory Superalloys

The current processes for protecting high temperature parts of turbo engines in most cases rely on two methods: thermochemical and PVD methods. The fundamental principles and, in particular, the application conditions are very different for these two methods. In general, however, all of the methods involve the formation of coatings high in aluminum content which ensure the effective protection of treated parts against corrosion at high temperature because of the formation of a very thin but continuous and self-generating film of very stable refractory oxides.

The thermochemical protection methods, in most cases "powder" methods, are essentially based on deposit in a halogen environment and diffusion of one or several metallic elements. They may be applied either in a single operation performed at high temperature (1,000-1,100°) using controlled activity methods, or in two independent, successive operations -- deposit at a moderate temperature (750-900°C) followed by out of pack rediffusion at higher temperature. These are high activity methods. The thermochemical protection method may also use successive diffusion, involving different operations, of several protective elements; for example, an initial diffusion of chrome and tantalum deposited in controlled amounts, followed by diffusion of aluminum following a method of controlled or high activity. On the other hand, it can be used on pieces first coated electrolytically with thin deposits of noble metals such as platinum or rhodium.

In any event, the purpose of making complex diffusion alloys

is to finally obtain protective coating with improved resistance to corrosion, and possibly better ductility in comparison with the resistance of coating obtained solely by aluminization.

PVD or overlay protection methods involve physical depositing: cathode spraying, ion-plating, plasma, etc of special complex alloys generally containing a dispersoid element such as yttrium the composition of which is practically independent of the nature of the substrate which it coats. PVD coatings, whose generic name is M-CrAlY, basically involve the combining in various proportions of the elements of aluminum, chrome and yttrium with one or several base metals, most often nickel and cobalt.

At the present time thermochemical protection methods are the most popular [5,6]. In fact, the majority of these methods have the advantage of having a relatively low cost of production and they make it possible to obtain protective coating of a uniform and predetermined thickness with a high degree of reliability, while only slightly affecting the mechanical strength characteristic at high temperature of the materials treated. So it is in general with the thermochemical protection methods developed at ONERA [7], methods whose principles and overall characteristics are outlined in Table 1. Fig. 1 shows a technical setup for applying these methods.

The protection techniques using chromaluminisation, tantalisation and silycralisation are well known at the present time. Besides the use of "non-wearing" deposit materials, one of the common characteristics of these methods is the establishment in situ of an operational rediffusion barrier. The much more recent DE 77 method, which until recently has not been discussed in the literature, basically involves the initial establishment of a ductile preliminary coating of an ordinary nickel-chrome compound (82/18 - 80/20 plus additives, in particular traces of

Table 1. General Characteristics of ONERA Thermochemical Techniques for

Protecting Refractory Superalloys

Technique	General Principles	Materials to be protected	Compatibility with the SF method	Overall results
Chromaluminization (controlled activity)	One-step diffusion of aluminum and chrome	Nickel or cobalt based superalloys	No problems	Very good resistance to oxidation and sulfuration
High activity aluminization	Deposit of aluminum in the presence of chrome + out of pack rediffusion	Nickel based superalloys	Possible, but not as a rule	Good resistance to oxidation
Sylcralization and tancrylisation	Duplex treatments a) moderate chromisation or tantalisation in the presence of lanthanides (5-30 microns) b) chromaluminisation ¹ or aluminisation ²	Nickel based superalloys	No problems if the final operation is "with controlled activity"	Very good resistance to oxidation; increased resistance to sulfuration
DE 77	Triplex treatment. Chemical depositing of nickel-boron, thermally deborided (5-30 microns as a rule), then silycralization or tancralization	Nickel or cobalt based superalloys, oriented eutectics, dispersed phase alloys	No problems if the final operation is "with controlled activity"	Excellent resistance to oxidation and sulfuration; particularly high stability and ductility of the coatings

1. e.g. controlled activity method

2. e.g. high activity method

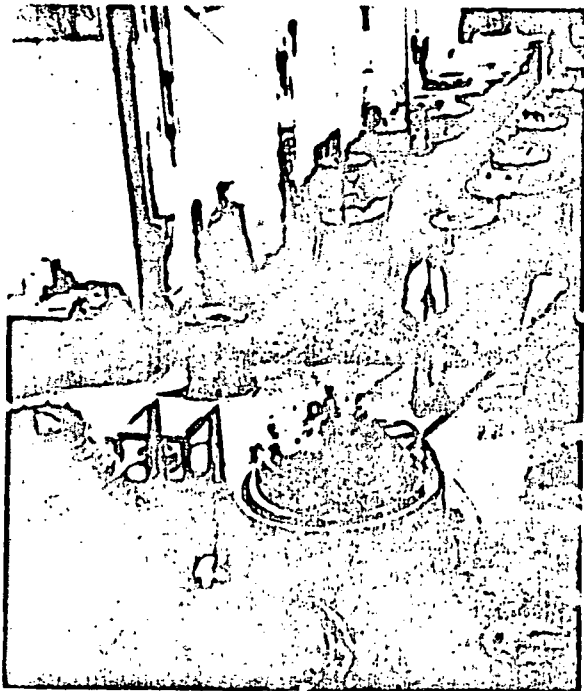
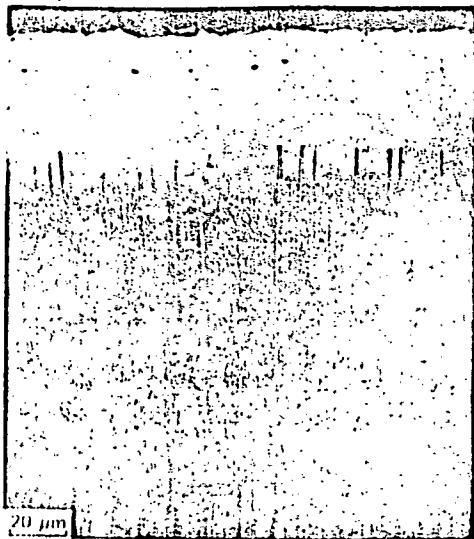


Fig. 1. Type of setup allowing application of all of the ONERA thermochemical protection or assembly techniques (partial view) -- Alloy surfaces, Wilmington

heavy elements) on parts which ultimately are to be protected. using traditional methods (controlled activity chrom-aluminisation, high activity aluminisation, etc.). The preliminary coating, the thickness of which is very uniform and in most cases ranges between 10 and 25 microns, is obtained by chemically depositing nickel-boron in an aqueous solution, followed by a deboriding-prediffusion operation carried out in a simple manner in a halogen atmosphere at 850° , then followed by a chrome alloy transformation treatment using thermochemical means (moderate chromization, doped with lanthanides).

The DE 77 protection technique can be very generally applied. It is suitable for refractory superalloys, oriented eutectics, dispersed phase alloys, etc. By means of this technique ductile coatings can ultimately be obtained. The thickness of these coatings can be predetermined and is very uniform. They are stable in use and have a particularly high resistance to oxidation and sulfuration at high temperatures when subject to thermal cycling. Since no operations involving the application of the DE 77 method have been carried out at a temperature greater than $1,050^{\circ}\text{C}$ -- except in special cases -- the effect of the treatment on the creep strength characteristics of the parts can in most cases be considered negligible.



The results obtained by using the DE 77 method can be seen by looking at Figs. 2-4. These pertain to a particularly difficult and so far unsatisfactorily solved problem, in this case the protection of COTAC type carbon fiber reinforced oriented eutectics.

Fig. 2. Basic hanging structure characteristic of the DE 77 protection treatment: example COTAC 74 -- direction perpendicular to the fibers



Fig. 3. Structure of a DE 77 coating applied on COTAC 74: 3A -- direction parallel to the fibers; 3B -- direction perpendicular to the fibers.

/22-4

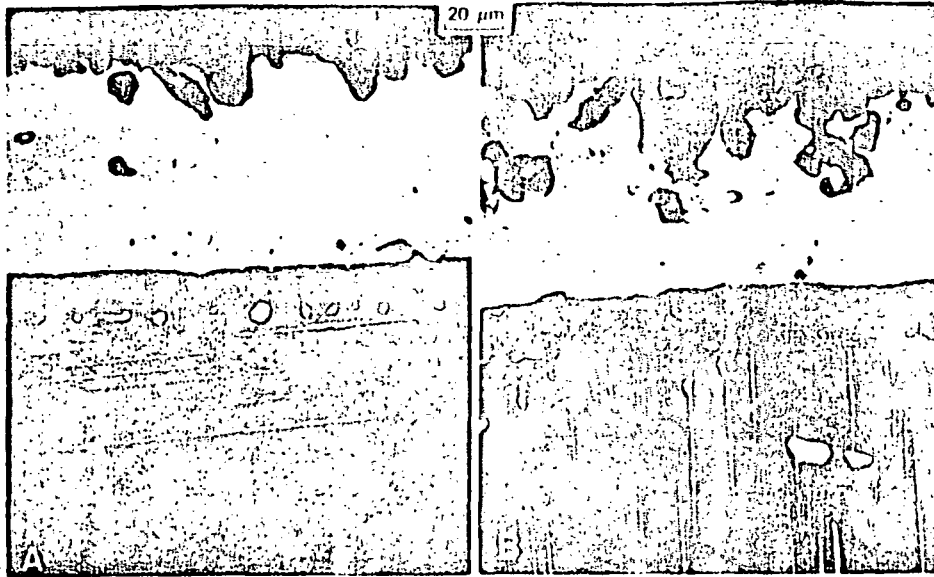


Fig. 4. Structure of a DE 77 coating applied on COTAC 74 following an oxidation test with harsh thermal cycling for 500 hours at 1,130°C in air: 4A -- Direction parallel to the fibers; 4B -- Direction perpendicular to the fibers. Note that there is almost no change in the initial thickness of the coating.

With PVD protection methods it is possible to coat the surfaces of parts to be protected with coatings whose thickness is in principle unlimited. The composition of the coatings is homogeneous and can be adapted to the composition of complex materials which have an uneven resistance to corrosion at high temperature [8,9]. On the other hand, PVD protection methods present several major drawbacks. Besides a high cost of production, these drawbacks include a low power of penetration and, as a rule, deficient ductility, and a tendency to rediffuse in use at high temperature which can result in a significant reduction in creep resistance of the protected parts [10].

The effectiveness and, in particular the stability of protective coatings applied by the PVD method can be appreciably improved by combining such a method with an initial coating

operation using thermochemical means, such as the diffusion of limited amounts of chrome, aluminum and chrome or chrome and tantalum [11]. In this way, a general preliminary coating of all of the surfaces of the parts to be protected can then be obtained. The particular type of nickel-chrome 80/20 + additives base layer which corresponds to the basic nature of the DE 77 method, as well as the thin but uniform coatings which can ultimately be obtained as a result of using the method present themselves a priori as types of pre-coatings which are particularly effective in the case of parts to be protected using the PVD method.

The final application of a supplementary coating treatment /22-5 using thermochemical means, such as chromaluminisation, on parts basically protected by the PVD method is, on the other hand, well known. In various particular cases using this method it is possible both to improve the quality and homogeneity of the surface regions of the coatings and to ensure the coating and thus the protection of areas of parts which could not be reached by the PVD coating treatment [12].

2. Principle, Basic Arrangements and Possible Overall Application Conditions of the ONERA-SF Method

A. Principle

The principle and aim of the SF method is to ensure the protection of all of the external and internal surfaces of cooled parts (in general, rotor blades or stator blades) subjected to the effects of corrosion or cracking in a corrosive environment, no matter how complex the internal shape of the parts to be coated. This is to be done in a simple and reliable manner, in most cases with a single operation using thermochemical means. Another objective is to specify treatments which allow the application of protective coatings of predetermined thickness according to each

particular region of the parts, without any risk of clogging the orifices for the flow of coolant air, no matter how small their diameter, or of unduly reducing the size of such orifices.

The application of the SF method seems basically justified for protecting cooled parts constructed of superalloys very sensitive to oxidation or sulfuration, such as IN 100 or B 1900, especially when the cooling of the part is accomplished, at least in part, by ejecting air through very small orifices or through long, narrow channels: cooling by convection, impact film, or simultaneous combination of several of these methods.

B. Necessary Arrangements

The SF method involves two necessary characteristic arrangements. These can be set up on their own or in combination with other methods, depending on the particular case.

a) Initial separation of the parts to be protected from the treatment environment, at least in the zones where the cooling

air arrives or is ejected, by means of highly porous, ductile covers, the shape of which can be exactly adapted to that of the zones of the parts which they are supposed to cover: SF arrangement, Fig. 5.

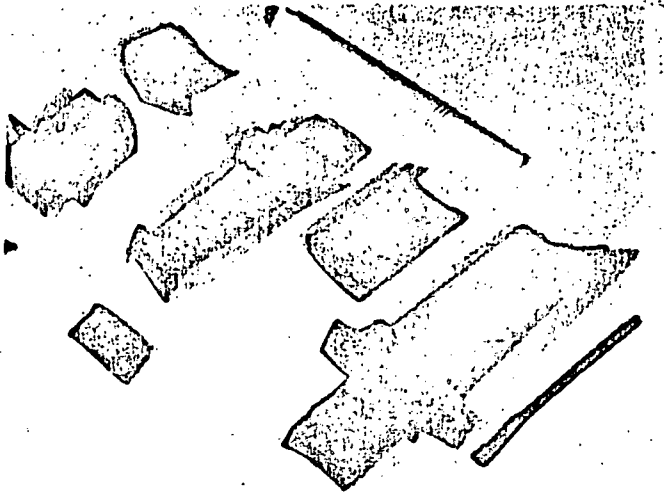


Fig. 5. Various cooled rotor blades and corresponding separation coverings for SF protection.

b. Initial injection of protective material into the interior of the parts to be protected. This is injected in predetermined amounts according to an arrangement which allows it to be used both gradually and

completely in the course of the coating treatment: SF + arrangement.

The separating covers are made of a thin, perfectly ductile sheet of nickel felt with an open porosity which is both very great and very fine. The sheet is transformed by duplex thermochemical treatment into a felt of nickel-chrome-aluminum alloy which is likewise very porous and ductile. The porosity of the material is completely open, on the order of 90%, and it generally ranges in thickness between 0.3 and 0.4 mm.

The porous material, which can be easily shaped either before or after thermochemical transformation preceded by moderate chromisation, does not show any significant elastic response, turns out to be practically neutral with respect to thermochemistry and ultimately cannot adhere to the surface of the protected parts, thus providing a particularly satisfactory type of separation.

The particular characteristics of the material, and more especially, its open porosity which is both very great and very fine makes it possible, on the one hand, to avoid any penetration of particles, no matter how fine, into the interior of the parts to be coated, and, on the other hand, to enhance the convection movements which ensure the circulation of vapors of carrier halides of deposit metals given off from the treatment charge. A local increase in density (partial or complete) of the material, which can initially be accomplished by simple grinding, makes it possible, on the other hand, to ensure, if necessary, a controlled reduction or, at the limit, suppression of the convection currents. The latter arrangement can be used either to obtain coatings of appreciable thickness on certain specific compartments just of special cooled parts or to help give extra protection both on inside and outside surfaces.

The possible initial incorporation of a predetermined and

completely consumable amount of added protective element in the interior of the parts to be protected -- necessary in different cases to ensure a relay action of metallic halide vapors given off by the treatment charge properly so called -- most often involves a sandwich type material with an aluminum-chrome base. Depending on the case, this material generally consists either of sections of a thin sheet or of section of fine aluminum wire coated with chrome, in most cases deposited by electrolysis for a well defined ratio by weight of chrome to aluminum. The sections are put into the interior of the parts to be protected in amounts corresponding to the final result being sought. It is also possible, at least in certain cases, to use particles of aluminum which have been electrolytically chromed or anode oxidized which are then injected at the start by means of pastes or gels which can be eliminated at high temperature without the formation of harmful residues.

By initially depositing chrome on the surface of the aluminum /22-6 it is possible to prevent flow at high temperature and to keep the metal substrate from forming drops with a low melting point. This thus prevents the drops from resulting in a coating of nonuniform thickness or places of local corrosion in the liquid phase of the surfaces of the material treated. Moreover, this deposit also helps to ensure under the best conditions that the protective elements added, chrome and aluminum, are added and diffused gradually but completely by the end of the operation.

C. Possible Application Conditions

In principle, it appears possible to apply the SF method in a general way combined with any technique whatsoever of thermo-chemical protection using powder or a purely gaseous phase involving different additive elements.

In fact, the use of the SF method seems most interesting and

turns out to be most effective in controlled activity protection processes which involve, at least in part, the use of aluminum as the protective diffusing element. Examples of this are the chromaluminisation method of ONERA and the Co-Dep method of General Electric.

The SF method, possibly combined with the supplementary arrangement described above, can be applied, without modifying any of the basic principles, to protection treatments properly so called; on the one hand in the case of initially untreated parts, and on the other in the case of parts initially coated by electrolytic, thermochemical or PVD methods.

In the case of protective coatings involving separate layers obtained by successive application of at least 2 identical or different operations certain particular preparation arrangements for the parts appear necessary in most cases.

Thus, successive treatments will be required to provide protection using solely the thermochemical method -- chromaluminisation, for example -- for rotor blades which are to be cooled by the presence of a large number of very fine perforations and whose external surfaces are to be protected by very thick coatings, while thinner coatings are to be used on the surfaces of the cooling orifices and the internal surfaces of the rotor blades. In similar cases the parts can be perforated after applying the first treatments, such as chromaluminisation or sylcralisation, which in themselves practically amount to obtaining a very thick external coating and can be accomplished in a way which in itself is traditional. Supplementary protection treatment for the internal surfaces then requires merely the use of at least SF arrangements.

An analogous perforation process coming after the supplementary

protection treatment by thermochemical means according to the SF method can also be considered in the case of parts initially coated by the PVD method instead of being protected by diffusion.

On the other hand, the application of at least one SF arrangement, in the case of certain types of cooled pieces, insures an overall or only internal precoating designed ultimately to improve the corrosion resistance of blades whose external surfaces are intended to be protected basically by the application of PVD methods. It is possible to initially limit a preliminary aluminum based coating only to the internal surfaces of cooled parts and to the surfaces of possible air ejection orifices in a simple way by using the SF arrangement involving the introduction of combined consumable elements such as chromed aluminum. Then, depending on the case and the intended goal, the parts to be treated can be heated either in a purely gaseous phase or in a neutral or active powdery environment, for example, in the latter case, cementation powder for moderate chromisation which, during the same operation, insures the application of a coating rich in chrome on the external surfaces of the parts to be coated.

In a very general way it appears essential to state that the making of protective coatings on the internal surfaces of tubular or perforated parts inevitably amounts to a uniform and predeterminable increased thickness which corresponds to approximately half of the thickness of the coating properly so called. Such an increased thickness, in itself easy to compensate for initially, can possibly be used advantageously to obtain very fine perforations from perforations which initially have a larger diameter and because of this are easier to make.

3 - Analysis of a Few Results Obtained Using SF Arrangements

Figs. 6 and 7 show different types of parts from the forward stages of turbo engines protected only by thermochemical methods or by a combination of different protection methods, together with the SF method. These are parts cooled by convection, film, impact etc. They reveal the large variety of cases which have already been studied. No particular internal shape of the parts seems in itself to pose any insurmountable problems.

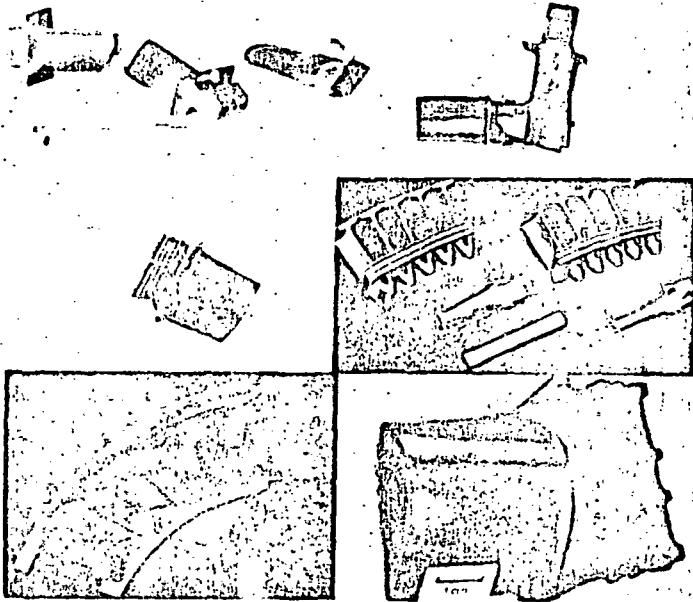


Fig. 6. Various cooled turbo-jet parts protected by the SF method.

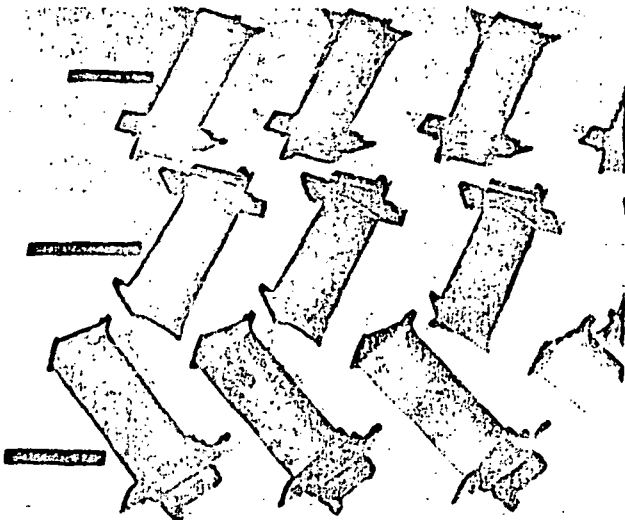


Fig. 7. Rotor blades of an industrial power turbine protected by the SF method (refractory alloy IN 100: chromaluminisation, depending on the external surfaces of the blade and the surfaces of the orifices which emit the cooling air).

By looking at the micrographs shown in Figs. 8-14 we can see the results which were obtained in different cases in an already predetermined and reliable way.



/22-7

Fig. 8. Structure of the coating of a cooled rotor blade of B 1900 protected by SF chromaluminisation, for coating of varied thicknesses depending on the external surfaces of the blade and the surfaces of the orifices which emit the cooling air.

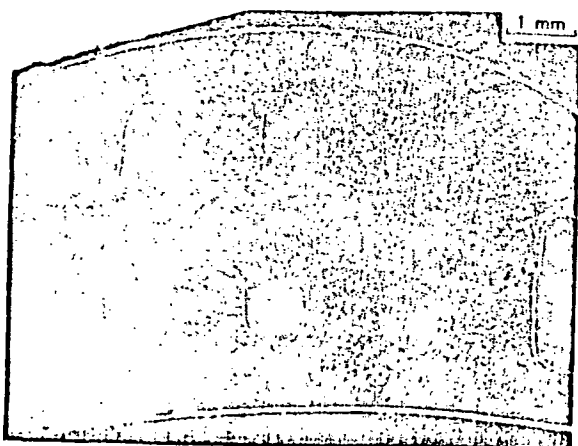


Fig. 9. Structure of the external and internal coating of a cooled rotor blade made of MAR 002 protected by SF^+ chromaluminisation -- midpoint cross-section.

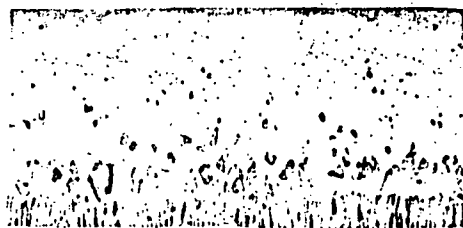
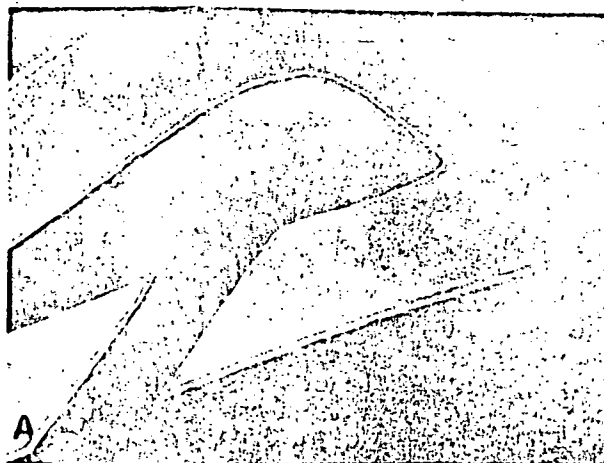


Fig. 10 (right). Structure of the external coating and internal coating of a cooled rotor blade made of Nimonic 108 protected in a general way by SF^+ chromaluminisation. 10A: Overall view. 10B: Detail of the structure of the external coating. 10C: Detail of the structure of the internal coating. Midpoint cross-section.



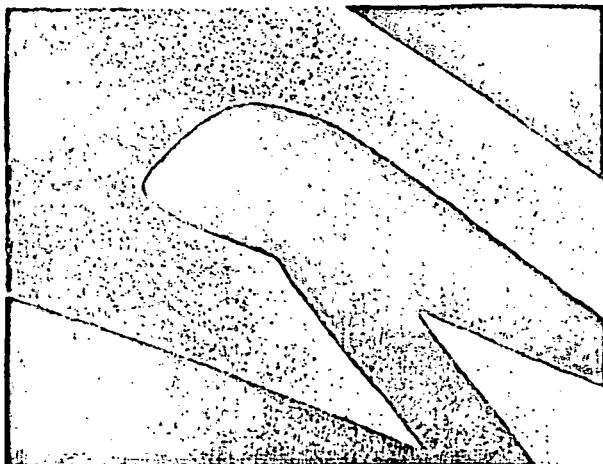


Fig. 11. Structure of the external coating and internal coating of a cooled rotor blade made of Nimonic 108 protected by SF chromaluminisation only on the leading and trailing edges. Trailing edge, midpoint cross-section [12].

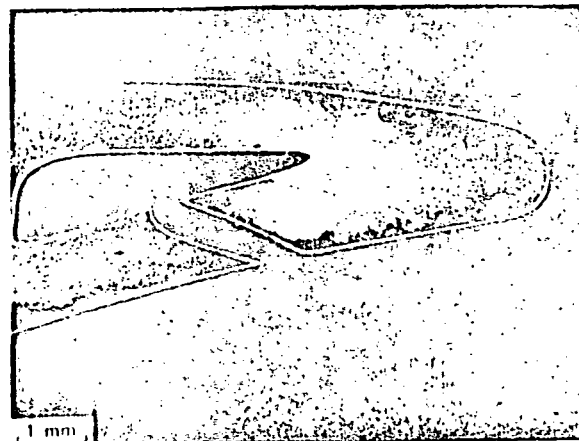


Fig. 12. Structure of the external coating internal coating of a cooled rotor blade made of Nimonic 108 protected by SF sylvralisation. Midpoint cross-section.



Fig. 13. Structure of the surface regions of the external coating obtained on a cooled blade made of B 1900 with an initial coat applied by the PVD method (Cocrally of P.W.A.) followed by a coating applied by SF chromaluminisation.

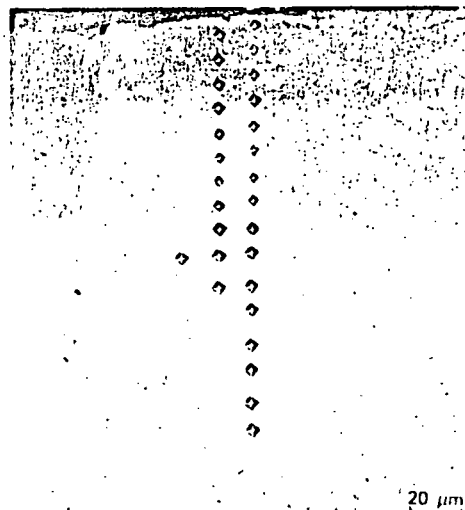


Fig. 14. Structure of the surface regions of a sample of IN 100 protected by SF chromaluminisation following a very thin electrolytic deposit of platinum.

Generally speaking, the thickness of internal coatings on cooled parts applied by using the SF method in most cases is found to range between 10 and 30 microns. The thickness of coating which are supposed to insure the protection of the external surfaces of the parts usually ranges between 30 and 100 microns. If one refers to a unit of coating thickness corresponding to a specific value, for example 20 microns, the quality of corrosion resistance at high temperature under the effects of thermal fatigue for internal surface coatings appears to be at least equal to the quality of coatings for external surfaces obtained by using the best traditions protection processes involving thermochemical methods. In particular, the internal coatings do not show an liability to scaling in an oxidizing environment at high temperature, and they effectively protect the substrate from the effects of thermal fatigue. The particularly high level of corrosion resistance of internal coatings and their lack of sensitivity to scaling are easily explained by the fact that such protective coatings essentially consist of sub-stoichiometric "aluminides" with regard to the exact definition M-Al, the corresponding diffusion alloys in addition containing some chrome throughout their entire thickness and being in an a priori favorable compression state.

A look at Figs. 8-14 does not seem to justify any detailed comments, since such comments could only recount what has already been said.

Fig. 15, by contrast, refers to a special case, in this case protection against corrosion and especially against the clogging of post-combustion injection strips. In a similar case, which requires only in a general way the supplementary SF arrangement, the presence of the internal coating makes it possible at least to considerably reduce, if not completely eliminate, the appearance and development of deposit phenomena and the growth of seeding

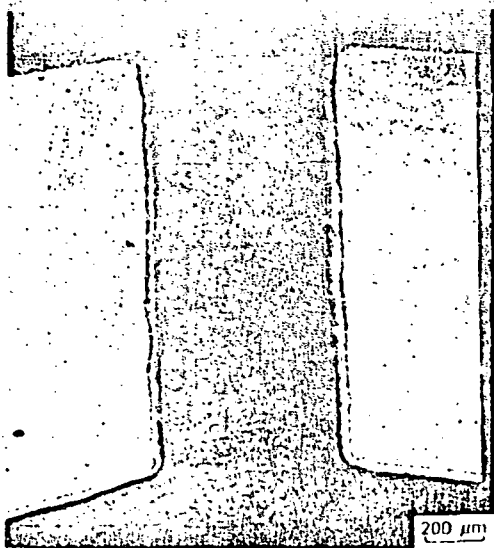


Fig. 15. Structure of the surface regions of a hole in a post-combustion injection strip made of Inconel protected by SF⁺ chromaluminisation.

sites for carbon-based soots which can ultimately lead to local or widespread blockage of the injectors.

Conclusions

/22-9

The results which have already been obtained on real parts by using the SF coating technique for cooled components with a particularly complex internal shape seem capable of making a worthwhile contribution to the development and safe use of advanced turbo engines which are essentially characterized by very high turbine input temperatures.

The very positive collaboration which was established between the ONERA Laboratory and different manufacturers or users of the parts in question is in any case one of the primary reasons which help the SF method move quickly beyond the stage of initial application on test samples or scale models, thus allowing this method to be applied from now on in assembly line production.

REFERENCES

1. Esslinger, P and Huff, A, "Development of materials used in gas turbine engines," Rev. Int. Htes Temp. 12, 172-185 (1976).
2. Stringer, J., "Hot Corrosion in Gas Turbines," NTIS Contract F 33615-71-C-1067, (June, 1972).
3. Armstrong, F.W., "Tomorrow Power," Flight International, 113-117 (Jan. 1977).
4. MacGreath, C.G., "The role of injected salts in hot corrosion," T.I.M.E. (G.B.), 88, 145-149 (1976).
5. Morre, V.S., Brentnall, W.D. and Stetson, A.R., "Evaluations of coating for cobalt and nickel base superalloys," NASA CR-72714, (July, 1976).
6. Seelig, R.P., "High temperature resistant coatings of superalloys," Reutte Congress (Austria) May, 1977 (preprint) (in process of being published).
7. Galmiche, P., "Applications of ONERA thermochemical techniques in aerospace construction," L'Aeronautique et l'Astronautique, 41, 33-42 (1973).
8. Boone, D.H., "Overlay coatings for high temperature applications," AIRCO TEMESCAL, Jan., 1976.
9. Deadmore, D.L., "Oxidation of cocraly and aluminized coatings in high velocity gases," NASA TN-D-6842-E 6809 July, 1972.
10. Betz, W., Huff, H. and Track, W., "Evaluating protective coatings against hot gas corrosion and gas turbine blades," Z.F. Werkstofftechnik [J. of Materials Technology], 5, 161-196 (1976).
11. Galmiche, P., "The ONERA thermo-chemical techniques," Metal Forming, 3 (1968).
12. Galmiche, P., "Corrosion of refractory superalloys exposed to combustion gases at high temperature," Trattamenti dei Metalli, 6, 27-35 (1973).